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PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ____

Project No. A-4105 GTRI/~~GIT~~ DATE 2 / 24 / 85

Project Director: E. O. Rausch ~~School~~/Lab RAIL

Sponsor: U. S. Army Missile Command
Redstone Arsenal, AL

Type Agreement: P. O. DAAH01-85-P-2868

Award Period: From 2/7/85 To 4/30/85 (Performance) 4/30/85 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 10,000	$ 10,000 (NTE)
Funded:	$ 10,000	$ 10,000

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Data Processing Package Development for Strain Sensing OTDR

ADMINISTRATIVE DATA

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Defense Priority Rating: DO-A2

Military Security Classification: Unclassified
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached ---- Supplemental Information Sheet for Additional Requirements.

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FORM OCA 4:383

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 7/10/85

Project No. A-4105 ~~XGHXXX~~/Lab RAIL-AD

Includes Subproject No.(s) N/A

Project Director(s) E. O. Rausch GTRC / ~~GIT~~

Sponsor USA MICOM

Title Data Processing Package Development for Strain Sensing OTDR

Effective Completion Date: 4/30/85 (Performance) 4/30/85 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. N/A Continued by Project No. N/A

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Each transmittal of this document outside the Department of Defense must have prior approval of controlling office (AMSMI-RGF)
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) A-4105	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Georgia Institute of Technology Georgia Tech Research Institute 6b. OFFICE SYMBOL (If applicable) RAIL	7a. NAME OF MONITORING ORGANIZATION U.S. Army Missile Command
6c. ADDRESS (City, State and ZIP Code) Atlanta, Georgia 30332	7b. ADDRESS (City, State and ZIP Code) AMSMI - RLG/Ruffin Redstone Arsenal, Alabama 35898
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Missile Command 8b. OFFICE SYMBOL (If applicable) AMSMI-RGL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAH01-85-P-2868
8c. ADDRESS (City, State and ZIP Code) AMSMI - RGL/Ruffin Redstone Arsenal, Alabama 35898	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT NO.
11. TITLE (Include Security Classification) Strain Sensing OTDR: Performance Evaluation	

12. PERSONAL AUTHOR(S) RAUSCH, E. O.			
13a. TYPE OF REPORT Final Technical Report	13b. TIME COVERED FROM 02/07/85 TO 04/30/85	14. DATE OF REPORT (Yr., Mo., Day) June 1985	15. PAGE COUNT 12
16. SUPPLEMENTARY NOTATION N/A			

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Optical Fiber   Optical Time Domain Reflectometer
Strain Sensor

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report discusses the performance of a strain sensing optical time domain reflectometer using multimode fibers. The output voltages of the instrument are converted to phase changes and related to fiber strain by means of a calibration curve. Phase fluctuations observed during the calibration phase provided an estimate of the strain sensitivity. The influence of signal amplitude fluctuations on strain was also evaluated. A method of correcting phase fluctuations is discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

FINAL TECHNICAL REPORT
Georgia Tech Project A-4105

STRAIN SENSING OPTICAL TIME DOMAIN REFLECTOMETER: PERFORMANCE EVALUATION

by
Dr. E. O. Rausch

Contract No. DAAH01-85-P-2868

Prepared for:

Commander
U.S. Army Missile Command
Attention: AMSMI-RGL/Ruffin
Redstone Arsenal, Alabama 35898

Prepared by:

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Period Covered
February 7, 1985 through April 30, 1985

June 1985

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SECTION 1

INTRODUCTION

1.1 OBJECTIVES

The Radar and Instrumentation Laboratory of the Georgia Tech Research Institute, working under U.S. Army Missile Command (MICOM) contract DAAH01-85-P-2868, initiated a two phase research program to design, construct, and test a strain sensing optical time domain reflectometer (OTDR). Phase I, conducted during February through August of 1984, dealt with the initial design and construction of the instrument.(1) System testing was conducted during Phase II. Only the results of Phase II are documented in this report.

1.2 BACKGROUND

Recent developments within the fiber optic guided missile (FOG-M) program have identified a need to know both the strain value and location during fiber payout in order to arrive at a set of fiber strength specifications. The fiber peel-off point is a prime suspect for harboring the maximum strain during the payout period, but no concrete experimental evidence is presently available to disclaim or confirm this hypothesis. The solution to this confirmation problem is twofold, requiring (1) an instrument that combines strain measurement with optical time domain reflectometry and (2) a sophisticated measurement/analysis approach to retrieve the desired information from the measured data.

The Georgia Tech Research Institute developed an instrument, the strain sensing OTDR, which could be employed for this experiment. The design is based on the principle of RF interferometry which does not require a single mode fiber, and for this reason, the strain sensing OTDR is ideally suited for the fiber optic guided missile program. The output intensity of the optical source is modulated with an RF signal. The modulated optical signal is then routed through a sensing fiber, redetected with an intensity sensitive

1. E. O. Rausch, "Strain Sensing Optical Time Domain Reflectometer", U.S. Army Missile Command Contract No. DAAH01-83-D-A013, Final Report, July 1985.

photodiode, and combined with the reference signal in I and Q mixers. The output voltage of the mixers is sensitive to the RF phase shift between the reference and the sensor signal. The RF phase shift is a function of the optical propagation speed which, in turn, is proportional to the strain in the fiber. Reflection points can be introduced within the fiber to determine the integrated strain separately for each fiber section by operating the strain sensor in a pulsed mode. In this pulsed mode, the principles of strain sensing and optical time domain reflectometry are combined in one instrument, hence the term strain sensing optical time domain reflectometer (SSOTDR). A block diagram of the SSOTDR is shown in Figure 1.

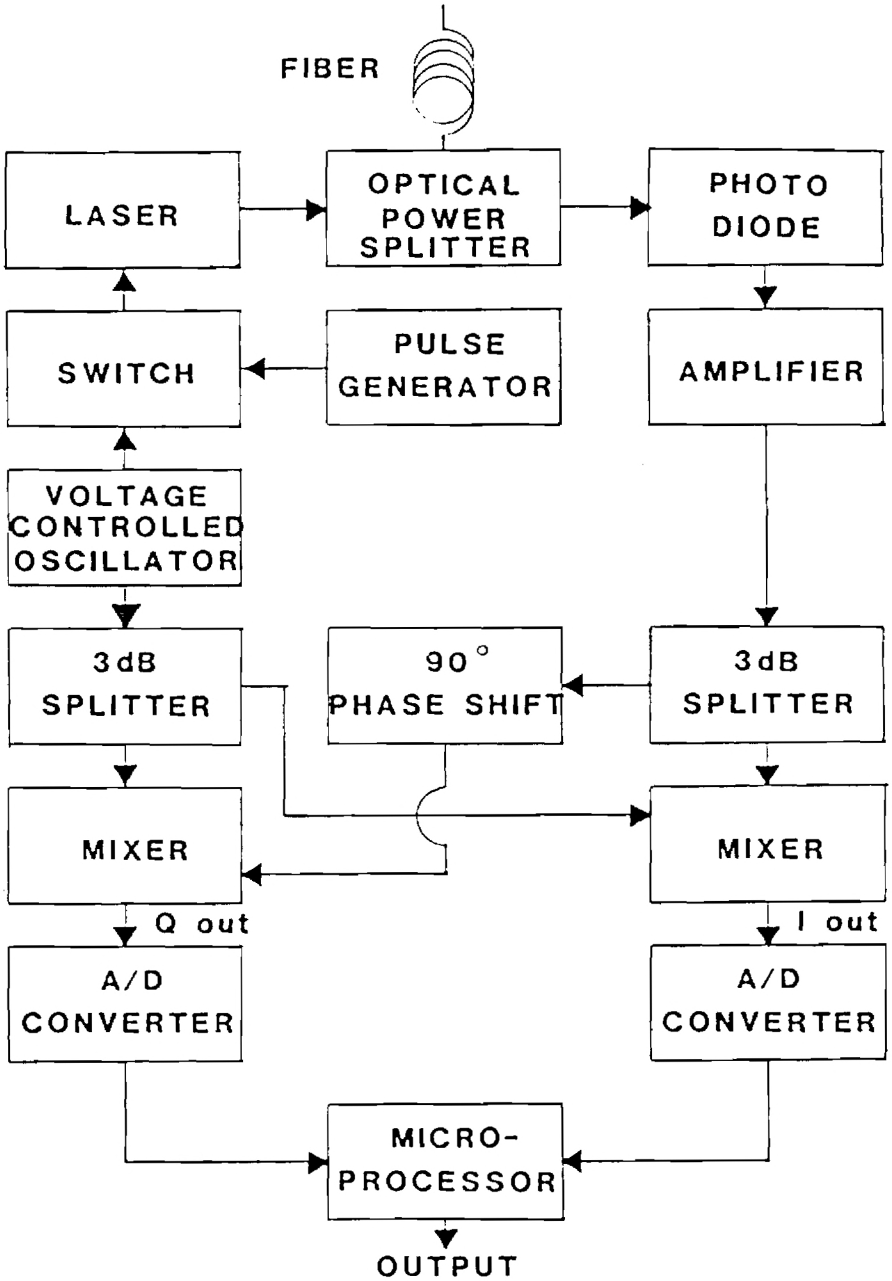

Figure 1. Block Diagram of Strain Sensing Optical Time Domain Relectometer.

SECTION 2
SYSTEM PERFORMANCE

2.1 SYSTEM OPERATION

The strain sensing OTDR is in some respects similar in operation to a radar: a pulse modulated sinusoidal waveform is transmitted through a medium, reflected by a scatterer, and received by the same system to extract information about the transmission medium and the scatterer. The amount of energy returned to the instrument is a function of the reflection coefficient of the scatterer and the absorption properties of the medium. Information on path length changes can be determined from changes in the phase difference between the transmitted and reflected signals. In the case of the strain sensing OTDR, the transmission medium is an optical fiber, and changes in phase difference can be related to changes in optical path length or fiber strain. The phase difference is computed from the output voltages of the two mixers, Q and I, (shown in Figure 1). If A_S and A_R are the mixer input voltages of the sensor signal and reference signal, respectively, and ϕ is the relative phase angle between the two signals, then the output voltage of the Q mixer is proportional to $A_S\ A_R \cos \phi$ and the output volage of the I mixer is proportional to $A_S\ A_R \sin \phi$. Q and I are commonly known as the quadrature (imaginary) and in-phase (real) components, respectively, of a complex two dimensional signal output vector containing both phase and amplitude information. Hence, the absolute phase difference ϕ is given by

$$\phi = \arctan (Q/I). \qquad (1)$$

Elongation of the sensing fiber changes the signal path length and causes a change in ϕ, referred to as $\Delta\phi$. Figure 2 shows the functional dependence of $\Delta\phi$ on fiber elongation in millimeters. Axial fiber strain is defined as fiber elongation in millimeters divided by the total unstretched fiber length in meters. Since the total fiber length in this experiment was 1 meter, the strain is given by the value on the horizontal axis times 10^{-3}.

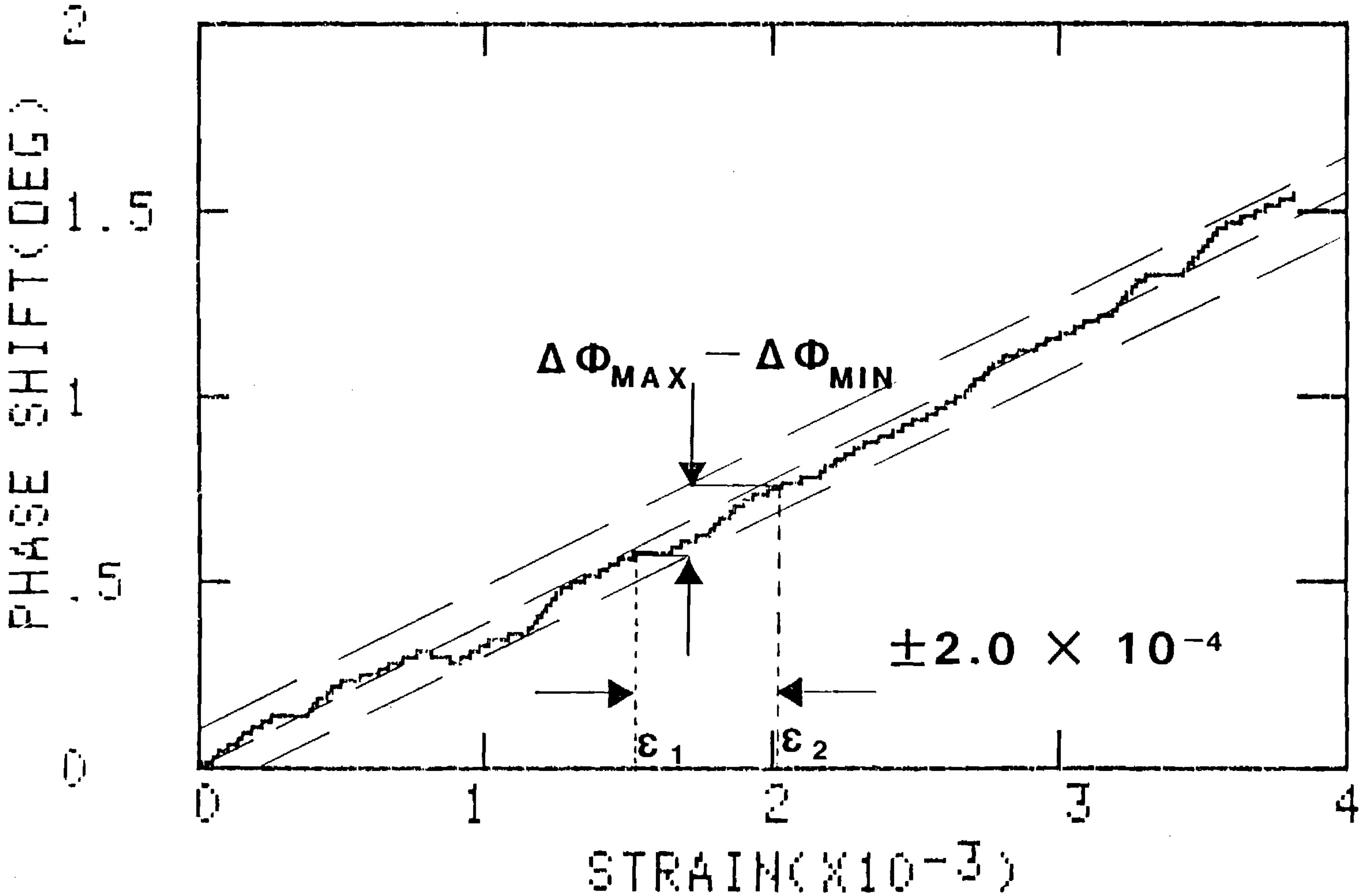

Figure 2. Phase Shift as a Function of Tensile Strain.

Fiber elongation was measured directly with a micrometer translation stage. Thus, Figure 2 represents a tensile strain calibration curve. Accuracy in tensile strain, as determined from the micrometer fine scale, was $\pm 1 \times 10^{-5}$.

2.2 STRAIN SENSITIVITY

A parameter of importance is the strain sensitivity of the SSOTDR, i.e., the minimum observable change in strain, also referred to as $\Delta\varepsilon$. $\Delta\varepsilon$ is a function of the maximum variations in $\Delta\phi$ due to system noise. The maximum variation of $\Delta\phi$ is ± 0.1 degree as determined from Figure 2. Its maximum value, $\Delta\phi_{MAX}$, would be interpreted by the computer as ε_2 and its minimum value, $\Delta\phi_{MIN}$, as ε_1. The difference $\varepsilon_2 - \varepsilon_1$ constitutes the required minimum observable change in ε ($\pm 2.0 \times 10^{-4}$) in order to ascribe this change to strain and not to instrument fluctuations. The $\Delta\varepsilon$ derived above is valid only for a period of about 1 minute, which is roughly the projected flight time of the FOG-M. Larger fluctuations than those indicated by $\Delta\phi_{MAX} - \Delta\phi_{MIN}$ have been observed in the past over periods of an hour, especially during instrument warm up periods, as is shown in Figure 3. Note that a time interval of at least 45 minutes is required to stabilize the electronic system of the SSOTDR.

Amplitude changes induced by modal noise in the input signals to the mixers were considered potential sources for the observed fluctuations in Figure 2. If so, the amplitude changes might be correlated with the observed $\Delta\phi$ changes in Figure 2. The I and Q data used to derive $\Delta\phi$ can also be used to compute a corresponding amplitude value, A, given by

$$A = \sqrt{I^2 + Q^2} = A_R \, A_S \; . \tag{2}$$

Figure 4 is a plot of amplitude versus fiber elongation. An examination of Figure 2 and Figure 4 does not, however, yield any correlation in the structures of the curves. This indicates that any changes in the amplitudes of the mixer input signals A_R and A_S appear equally in the Q and I components and, thus, will not affect ϕ in Equation 1. For this reason, an amplitude versus tensile strain calibration curve is not required.

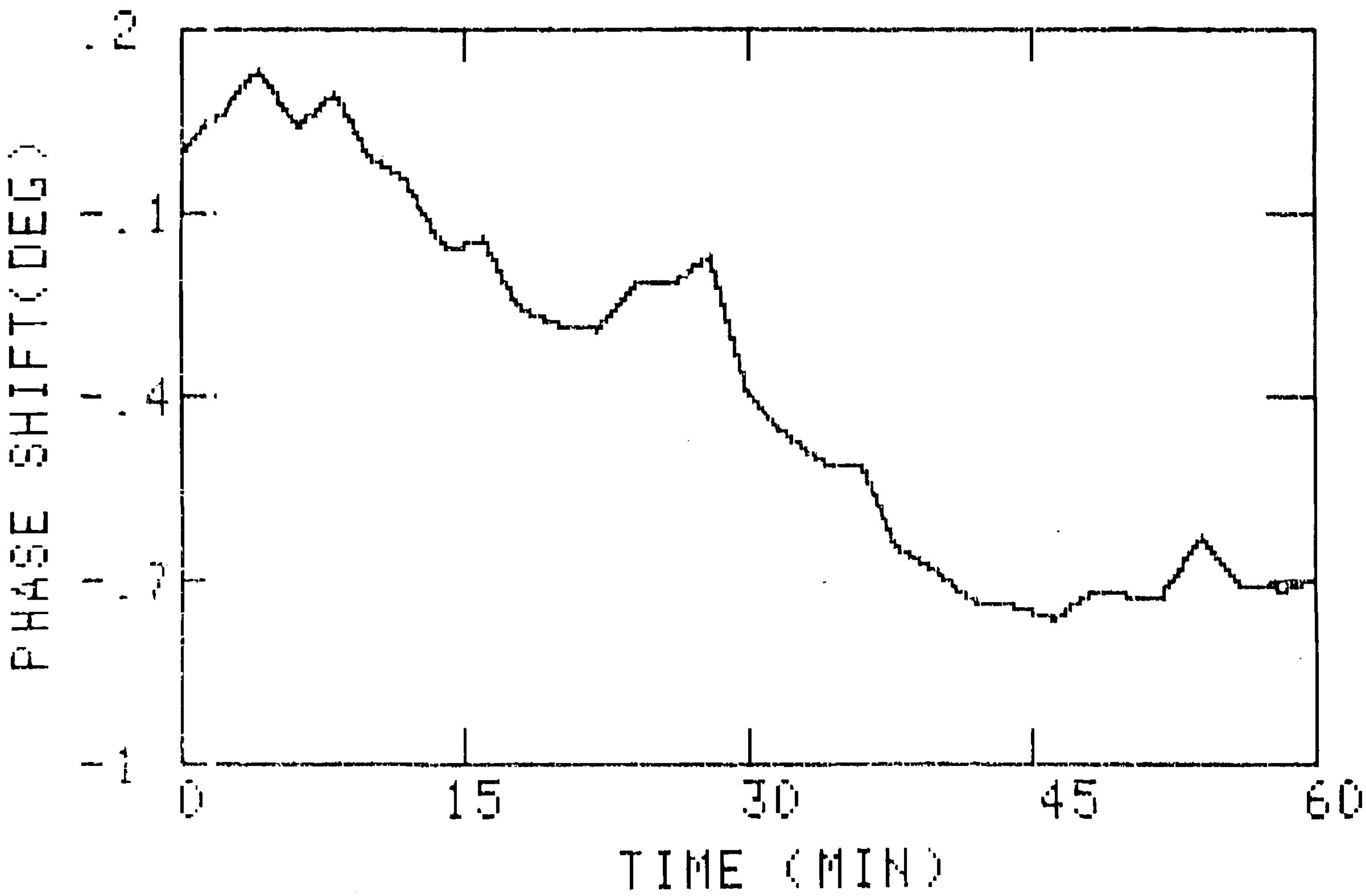

Figure 3. Phase Shift Versus Time During Instrument Warm Up.

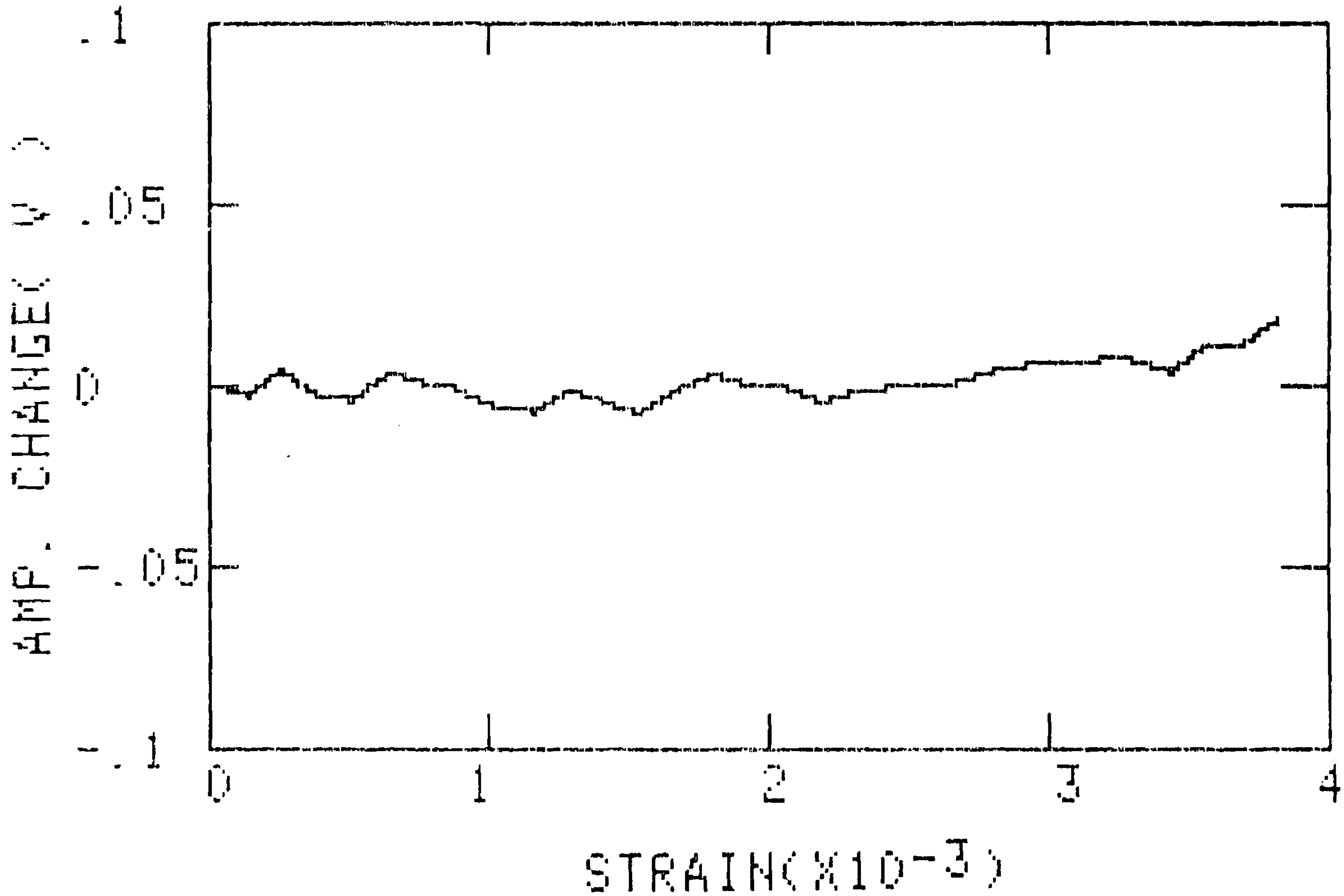

Figure 4. Amplitude Change Versus Tensile Strain.

The origin of the fluctuations are most likely due to amplitude-to-phase modulation conversions occurring within the electronic amplifiers or laser diode of the instrument. Corrections that minimize these fluctuation can be made by providing an optical signal return that is influenced only by the components within the instrument itself ("main bang"), not by the sensing fiber. The component required to yield both the sensing signal and the "main bang" is an optical power coupler, illustrated in Figure 5. Laser light is coupled into the 50 micron core fiber on the left side of Figure 5 and divided between the 35 micron and 50 micron fibers on the right side. The end facet on the 50 micron output fiber will serve as the reflector for the "main bang" whereas the 35 micron output fiber will be coupled to the sensing fiber. Signals returned through either output fiber will be automatically split. Half of the energy will be routed back to the laser diode; the other half will be detected with a photodiode.

A two-to-two splitter is fabricated by twisting 2 multimode optical fibers, whose polymer coatings have been removed, and applying heat to the twisted zone. As the twisted part of the 2-fiber array softens, tension is applied and a small diameter taper is formed. Optical power injected into one of the two input fibers will be coupled into both output fibers since they are all joined at the taper.

The mechanism for optical power coupling from one input fiber to two output fibers is depicted in Figure 5. Optical power residing in high order modes in the input fiber radiates into the cladding at the taper. The radiated light is then confined within the cladding until the output taper is encountered. At the output taper, the light is coupled to the core of each optical fiber. The optical power loss of such a coupler comprises an intrinsic splitting loss term of 3 dB and an excess loss component (typically 1 to 2 dB) that is a function of taper length, diameter, and uniformity.

Optical fibers having a 50-micron and 35-micron core and a 125-micron cladding diameter were used to fabricate the 2-to-2 fused biconical taper coupler now employed in the SSOTDR. Two optical fibers approximately 2 meters long were secured in a coupler fabrication device consisting of two wheels

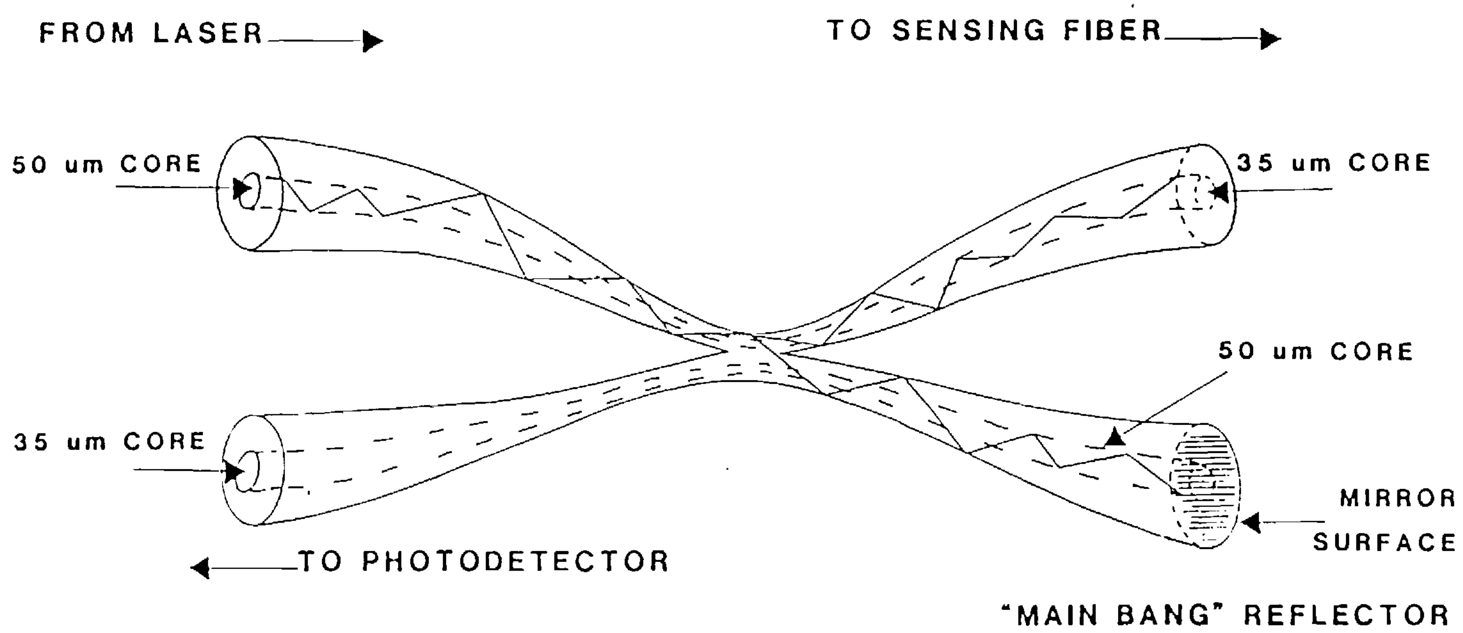

Figure 5. Optical Power Coupler.

that rotate in yokes; one wheel was mounted on a spring-loaded linear translation arm. The acrylate coating was removed from each fiber over a 5-centimeter zone centered between the two fiber-holding wheels by utilizng methylene chloride. The fiber-holding wheels were rotated to form a twist zone of 1 to 2 centimeters. Tension was applied by the spring-loaded linear translation arm. Optical power from an Aerotech helium-neon laser was injected into the 50 micron core input fiber. A mandrel-wrap mode stripping device was used to remove cladding and weakly-guided modes. The 35-micron core output fiber was then positioned for visual inspection of output intensity, while the 50-micron core output fiber was connected to a Photodyne Model 22XLA Fiber Optic Multimeter.

An oxy-propane torch was employed to heat the fiber twist zone. Tension was applied until nearly equal light intensity was emitted from each output fiber and the power reading from the output fiber attached to the photodiode indicated an acceptable excess loss. The fused biconical taper coupler was then secured within a machined aluminum enclosure by means of epoxy. The tapered region of the coupler was not allowed to contact the epoxy; this separation was necessary to ensure low insertion loss and minimize the chance of fracture at the taper zone. The measured excess loss was 2 dB.

2.3 BENDING STRAIN

Experiments were conducted to determine the magnitude of phase and amplitude change due to bending strain in the fiber. Although the phase changes were sufficiently large to be detected, they could not be differentiated from tensile strain on the basis of phase alone. A fiber bend is also accompanied by a decrease in amplitude depending on the radius of the fiber's curvature. For the curvatures expected during fiber pay out (> 1 cm) the amplitude changes were generally too small to make a distinction between tensile and bending strain. On the basis of this information, a bending strain calibration curve is useless unless noisy amplitude fluctuations can be minimized below the level observed with tensile strain.

2.4 CONCLUSIONS

Strain sensitivities of the SSOTDR ranged from -2.0×10^{-4} to $+2.0 \times 10^{-4}$. An improvement in these values is possible by (1) sensing the "main bang" return, (2) calculating the phase difference due to the "main bang," and (3) subtracting this phase difference which is due to instrument drift from the phase difference obtained from the sensing fiber. Amplitude changes in the signal do not affect the measured phase differences.